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13. ABSTRACT *(Maximum 200 words)*

Patterns of 40 to 80 Hz oscillation have been observed by researchers of this laboratory in the large scale activity not only of olfactory cortex, but also visual neocortex, and shown to predict the olfactory and visual pattern recognition responses of a trained animal. Similar observations of 40 Hz oscillation in auditory and motor cortex, and in the retina and EMG have been reported. It thus appears that cortical computaiton in general may occur by dynamical interaction of resonant modes, as we have long thought to be the case in the olfactory system. The oscillation can serve a macroscopic clocking function and entrain or "bind" the relevant microscopic activity of disparate cortical regions into a well defined phase coherent collective state of "gestalt". This can overide irrelevant microscopic activity and produce coordinated motor output. We have further evidence that the oscillatory activity is roughly periodic, but actually appears to be chaotic (nonperiodic) when examined in detail. If this view is correct, then networks with oscillatory and possibly chaotic activity form the actual cortical substrate of the diverse sensory, motor, and cognitive operations now studied in static networks. It must then be shown how those functions can be accomplished with oscillatory and

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chaotic dynamics. It is our expectation that nature makes good use of this dynamical complexity,.and our intent has been to search here for novel design principles that may underly the superior performance of biological systems in pattern recognition. These may then be applied in artificial systems to engineering problems.

FINAL TECHNICAL REPORT

Grant No. AFOSR-88-0286

2 December 1991

1 Introduction

Patterns of 40 to 80 Hz oscillation have been observed by researchers of this laboratory in the large scale activity not only of olfactory cortex, but also visual neocortex, and shown to predict the olfactory and visual pattern recognition responses of a trained animal. Similar observations of 40 Hz oscillation in auditory and motor cortex, and in the retina and EMG have been reported.

It thus appears that cortical computation in general may occur by dynamical interaction of resonant modes, as we have long thought to be the case in the olfactory system. The oscillation can serve a macroscopic clocking function and entrain or "bind" the relevant microscopic activity of disparate cortical regions into a well defined phase coherent collective state or "gestalt". This can overide irrelevant microscopic activity and produce coordinated motor output. We have further evidence that the oscillatory activity is roughly periodic, but actually appears to be chaotic (nonperiodic) when examined in detail.

If this view is correct, then networks with oscillatory and possibly chaotic activity form the actual cortical substrate of the diverse sensory, motor, and cognitive operations now studied in static networks. It must then be shown how those functions can be accomplished with oscillatory and chaotic dynamics. It is our expectation that nature makes good use of this dynamical complexity, and our intent has been to search here for novel design principles that may underly the superior performance of biological systems in pattern recognition. These may then be applied in artificial systems to engineering problems.

The focus of our work was to characterize mathematically the essential mechanisms and principles of operation of the mamalian olfactory neural network and evaluate its computation and pattern recognition capabilities. In this endeavor we have indeed discovered novel and powerful network architectures and learning algorithms.

Over the three and a half years of the grant, we published 13 papers, and gave presentations at 16 conferences. Network algorithms and architectures for pattern recognition have been constructed from neural models of the olfactory system, using the mathematical tools of dynamicl systems theory. These span a range from highly abstract to physiologically detailed, and employ the kind of dynamical complexity observed in olfactory cortex, ranging from oscillation to chaos.

2 Theoretical Work

A new class of learning algorithms for the storage of static and periodic attractors in recurrent analog neural networks was developed. Over the grant period, the original projection algorithm has been extended and refined in many ways. The seminal mathematical insight of the algorithm was that techniques of bifurcation theory for analysis of nonlinear dynamical systems could be inverted to produce precise techniques for synthesis of dynamical neural networks like that of the olfactory system.

A key feature of a net constructed by this algorithm is that the underlying dynamics is explicitly isomorphic to any of a class of standard, well understood nonlinear dynamical systems - a "normal form". This system is chosen in advance, independent of both the patterns to be stored and the learning algorithm to be used. This control over the dynamics permits the design of important aspects of the network dynamics independent of the particular patterns to be stored. Stability, basin geometry, and rates of convergence to attractors can be programmed in the standard dynamical system.

We were able to derive learning algorithms for content addressable memory storage of static and oscillatory attractors with analytically guaranteed storage capacity of N static and N/2 oscillatory attractors in an N node network. This is in contrast to the ESTIMATES of 4 N/ log N static attractors for an AVERAGE Hopfield network (nothing precise can be said for any individual Hopfield network). This was done with a simple learning rule

- a formula requiring a matrix inversion - for first and third order weights in a recurrent network architecture. There are no spurious attractors, and there is a Liapunov function in a special coordinate system which governs the approach of transient states to stored patterns.

Later work extended these results to allow guaranteed storage of multiple periodic spatiotemporal sequences of up to N/2 total Fourier components. We showed also that for orthogonal patterns, the projection learning rule reduced to a Hebbian outer product rule that allowed local incremental learning. In this last year we have shown that N/3 chaotic attractors may be stored in an N node network, and constructed networks with multiple static, periodic, and chaotic attractors all in the same network.

A new architecture called the projection network was developed that did not require the higher order weights (only 3 X N squared weights instead of N fourth) yet retained all the mathematically demonstrable capabilities of the previous architecture. This net was thus more suited to engineering applications. Unsupervised or supervised incremental learning algorithms for pattern classification, such as competitive learning or bootstrap Widrow-Hoff can easily be implemented in this architecture.

Network performance was demonstrated by application to the problem of real time handwritten digit recognition. An effective system with on line learning was written for the Macintosh. It utilizes static, oscillatory, and/or chaotic attractors of three kinds - Lorenz attractors, Roessler attractors, or attractors resulting from chaotically interacting oscillatory modes, which we call Ruelle-Takens attractors. This appears to be the first system which can use exclusively chaotic dynamics to accomplish pattern recognition.

On the more scientific front of biological modeling, the higher order network was refined into a biologically minimal network model of olfactory cortex with explicit excitatory and inhibitory neurons. This model assumed the least of known biological connections, and was shown to have the associative memory capacity of the systems above. We showed also that only N squared of the higher order weights between excitatory neurons were reqired for approximate pattern storage in this system.

3 An Industrial Application

In a parallel development by Freeman and Yao, a physiologically detailed olfactory system model was developed in software and hardware versions. Its features were derived from biological studies and bring the model closely into conformance with biological constraints. This model, which we call a KIII set, was tested in respect to artificially generated data set and then with a data set derived from an industrial source. The KIII model was "instructed" with examples from groups of objects to be classified, with use of a form of the Hebb rule to modify the connection weights. The interconnections were designed in accordance with the time multiplexing operation that enables connections to be made in large arrays of N coupled oscillators with 2-N rather than N-square connections.

The performance of the KIII model in classification of the members of this data set was compared with the performance of a Bayesian statistical approach, the Hopfield model, and a back-propagation model. Of the three classes of objects, those having a relatively high degree of symmetry were classified equally well by all of the approaches. The most difficult set of objects, which had a high degree of asymmetry and therefore a large amount of extraneous variance, were successfully classified only by the KIII model operating in a chaotic domain and not in a limit cycle domain. The results indicate that exploration of chaotic dynamics may be crucially important for the preprocessing of complex high-dimensional data sets prior to attempts at classification.

B i l Baird

Invited Talks and Conferences*

1988

First Annual INNS Meeting, Boston, Mass., September

Neural Information Processing Systems - Natural and Synthetic, Denver, Colo., November

1989

U.C. San Diego, Cognitive Science Dept., January

Chairman of session, Workshop on Neural Networks as Dynamical Systems, U.C., San Diego, Ca., February

Emergent Computation - Self-Organizing, Collective, and Cooperative Phenomena in Natural and Artificial Computing Networks, Center for Nonlinear Science, Los Alamos, N.M., May

International Joint Conference on Neural Networks, Wash. D.C., June

Neural Information Processing Systems - Natural and Synthetic, Denver, Colo., November

1990

Stanford University, Chemistry Dept., Palo Alto, Ca., March

Lawrence Livermore National Laboratory, Institute for Scientific Computing, Livermore, Ca., April

Chairman of session, International Joint Conference on Neural Networks, San Diego, Ca., June

Analysis and Modeling of Neural Systems 1, U.C. Berkeley, Ca., July

U.C. Santa Cruz, Mathematics Dept., September

Neural Information Processing Systems - Natural and Synthetic, Denver, Colo., November

1991

Plenary talk, Applications of Artificial Intelligence and Neural Networks, SPIE, Orlando, Fla., April

Stanford University, Artificial Networks Group, Palo Alto, Ca., April

Invited Speaker, Workshop on Complex Dynamics in Neural Networks, Vietri, Italy, June

*talk or poster given at all conferences listed

Bill Baird - Publications for AFOSR

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